

PATENT APPLICATION

TITLE OF INVENTION

Etalon Enhanced Saturable Reflector for Mode-Locked Lasers

INVENTORS

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RESEARCH OR DEVELOPMENT**

This invention was supported in part by grant number CA73368-03 from the National Institutes of Health. The Government has certain rights in the invention.

FIELD OF THE INVENTION

This invention relates generally to mode-locked lasers. More particularly, it relates to enhancement of saturable Bragg reflectors (SBRs) using a back side of the SBR substrate.

BACKGROUND ART

The type of passive mode-locker that has had the greatest recent impact is based on saturable absorption in semiconductor films. One type of saturable absorber device is known as a saturable Bragg reflector (SBR). An SBR generally comprises a Bragg stack disposed on a substrate. The Bragg stack typically contains alternating layers of narrow bandgap, e.g. Gallium Arsenide (GaAs), and wide bandgap, e.g. Aluminum Arsenide (AlAs), layers with a saturable absorber layer inserted in one of the narrow bandgap layers. The layers are usually deposited by metallo-

organic chemical vapor deposition (MOCVD) or molecular beam epitaxy (MBE). An alternative to semiconductor saturable absorbers formed by epitaxial growth (MOCVD, MBE) is to use films formed by simpler deposition methods (sputter, evaporation) that are commonly used for coating optical components. [Bilinsky, 1998] This approach is much less well developed at this time compared to the semiconductor material. The reflection characteristics of the SBR generally depend on the wavelength of the incident radiation. The saturable layer modifies the reflection characteristics of the SBR near a characteristic exciton wavelength. The absorber layer within the Bragg stack provides a non-linear reflectance as a function of fluence. The reflectance of such a stack tends to increase with increasing fluence and saturates as the fluence rises above a predetermined level. The reflectance is affected by an exciton effect of the saturable layer. This effect may be tuned, e.g. by changing the temperature of the substrate. Saturable Bragg Reflectors are described in detail in United States Patent 5,627,854 issued to Wayne Knox, which is incorporated herein by reference.

SBRs provide a nonlinear saturation response for mode-locking lasers. A mode-locked laser typically comprises a lasing medium such as Nd:YAG disposed in an optical cavity. A pump source, such as a diode laser pumps the lasing medium to produce stimulated emission of light. An SBR typically serves as one of the reflectors for the laser cavity. Optical pulses produced by the laser tend to have higher fluence and, therefore, lower loss at the SBR. Consequently, such a laser tends to favor pulse formation at high fluence.

The properties of the substrate of the SBR affect the performance of the laser. For example if the substrate transmits light, some light may reflect off both the front and back surfaces. Light reflecting from the back surface produces

feedback that interferes with light reflecting from the front surface and affects the performance of the SBR and mode-locked laser. Such interference effects have either been ignored in the prior art, because the front surface is much more reflective than the back surface, or viewed as detrimental to laser operation. Sometimes, SBRs are manufactured with substrates having polished back surfaces. Where the effect was not negligible, the prior art removed the effect by sanding the back surface to roughen it, thereby making it less reflective. The effect has also been observed to depend on the type of glue or solder used to attach the substrate to a supporting plate.

The pulses produced by a laser may be altered using an etalon. Etalons have been previously used to control the spectrum in mode-locked lasers. An etalon uses two parallel reflecting surfaces separated by a known distance. Interference of light reflected or transmitted from the two surfaces reinforces certain wavelengths of light, while tending to cancel out others. It is well known to use an etalon to affect the spectrum of a laser to lengthen or shorten optical pulses in a mode-locked laser. Alternatively the etalon may be used to optimize the relation between the temporal and frequency domains of the laser spectrum or adjust the distribution of power amongst the various modes of the laser. Prior art etalons have been separate discrete elements. Consequently, these etalons are difficult to implement in a mode-locked laser because they are difficult to align properly. Etalons must generally be temperature and vibration stable. In short, an etalon usually adds the complexity of construction and cost of a mode-locked laser.

A variety of passive mode-locks based on film technology have been developed or proposed recently. These are classified in the literature as saturable Bragg reflectors (SBR), semiconductor saturable absorbing mirrors (SESAM), anti-resonant

5 Fabry-Perot saturable absorbers (AFPSA), and hybrid saturable reflectors. AFPSA's were the first devices to use nonlinear semiconductor saturable absorption as a passive mode-locking technique. [Keller, 1992, Keller, 1996, Keller, 1993] An AFPSA device has a substrate upon which is applied a Bragg mirror stack, a saturable absorber in a buffer layer, and a surface coating. The thickness of the buffer layer is designed for anti-resonance. The surface coating is typically a partial reflector to control the field intensity in the absorber region, 10 although variants include an anti-reflection coating or no coating at all in which case the surface reflectivity was determined by the Fresnel reflectivity of the interface.

15 A hybrid saturable reflector consists of a substrate with an absorbing layer grown on the back surface (rather than on the top surface), then covered by a dielectric or metal mirror. [Alcock, 1999] In this approach. the laser field passes through the substrate but the interaction is benign so the only purpose of the substrate is to support the saturable absorber and mirror structure. No etalon effect is employed; in fact, the front 20 surface of the substrate is AR coated to avoid any possibility of etalon effect. Alternatively the front surface could be left uncoated or coated with a partial reflector to introduce etalon effects.

25 There is a need, therefore, for a low cost, simple, tunable, mode-locked laser having a saturable reflector that incorporates an etalon to control the laser spectrum.

OBJECTS AND ADVANTAGES

30 Accordingly, it is a primary object of the present invention to provide a saturable Bragg reflector having integral etalon tuning. It is a further object of the invention to provide a mode-locked laser with low cost, reduced complexity, and improved performance.

SUMMARY

These objects and advantages are attained by a Saturable Bragg Reflector apparatus comprising a substrate having a front surface and a back surface, and a Bragg stack, having a saturable absorber layer, attached to the front surface. At least one of the front and back surfaces has been modified to enhance an etalon effect due to interference of light reflecting from the front and back surfaces. Either or both of the surfaces may be modified, for example, by polishing or coating. The apparatus may also include means for adjusting an optical thickness of the substrate to tune the etalon effect. Such means may comprise a temperature control element, such as a heater, coupled to a temperature controller. The inventive apparatus may be incorporated into a mode-locked laser. Tuning the substrate etalon effect implements an inventive method for tuning a saturable reflector. The etalon tuning optimizes a relation between temporal and frequency domains of radiation incident on the SBR.

In embodiments of the present invention, the SBR device is monolithically integrated with a Fabry-Perot etalon fabricated in the same substrate. A temperature control circuit tunes and stabilizes the device operating point. It is the interaction of the etalon modes with the laser spectrum and the saturable absorber temperature which causes changes to the pulse width. The etalon typically has a free spectral range (FSR) of order 1 GHz or greater. The etalon thickness is generally large enough to give an FSR on order of the laser linewidth.

A specific embodiment of the invention comprises a device having a GaAs wafer substrate with structures on the front and back surfaces. On the front surface is a saturable Bragg reflector, consisting of a Bragg reflector stack and a quantum-well nonlinear absorption layer. On the back surface is a reflector,

which forms an etalon with the substrate and Bragg reflector. Thus the device integrates a passive mode-locker with an etalon which modifies the spectral content of the light to alter the pulse length produced by the mode-locked laser. In particular, the device is used to build a mode-locked laser with a flattened gain spectrum by suppressing the gain peak, thereby increasing the bandwidth and shortening the pulse length.

BRIEF DESCRIPTION OF THE FIGURES

- Fig. **1A** depicts a saturable Bragg reflector to the prior art;
 Fig. **1B** depicts a saturable Bragg reflector to a first embodiment of the present invention;
 Fig. **2** depicts laser according to a second embodiment of the present invention;
 Fig. **3** Depicts a graph of measured pulse length vs. temperature in a mode-locked laser using a monolithic etalon-enhanced saturable Bragg reflector of the type shown in Fig. **2**;
 Fig. **4**. Depicts a sketch of laser gain line shape juxtaposed with the etalon reflectivity spectrum (not to scale) for a mode-locked laser of the type shown in Fig. **2**;
 Fig. **5** depicts detailed views of the graph of Fig. **3** over two different temperature ranges;
 Fig. **6A** depicts autocorrelation and optical spectrum traces for an SBR operated with etalon enhancement; and
 Fig. **6B** depicts autocorrelation and optical spectrum traces for the SBR of Fig. **6A** operated with its back surface sanded to remove the etalon enhancement.

DETAILED DESCRIPTION

1. INTRODUCTION

Although the following detailed description contains many specifics for the purposes of illustration, anyone of ordinary

skill in the art will appreciate that many variations and alterations to the following details are within the scope of the invention. Accordingly, the following preferred embodiment of the invention is set forth without any loss of generality to, and without imposing limitations upon, the claimed invention.

Embodiments of the present invention integrate a passive mode-locker and an etalon for spectral shaping into a single monolithic device. In prior art mode-locker devices, the substrate is a benign element that serves only to support the mode-locker structure. In the embodiments of the present invention, the substrate is a key part of the device and serves to form an etalon that controls the spectral shape in laser operation. In embodiments of the present invention, the etalon is integrated with the mode-locker itself.

In embodiments of the present invention, the etalon is used for a different purpose and has a different construction than the anti-resonant etalon of the AFPSA of the prior art. Furthermore, the etalon in embodiments of the present invention does not contain a saturable absorber layer. The etalon serves to modify the laser spectrum rather than to control the field intensity in the absorber. The absorber is placed in front of the etalon rather than within it. The etalon is typically operated on-resonance rather than off-resonance.

The invention is an etalon-enhanced passive mode-locker and its use in a mode locked laser. The mode-locker consists of a saturable Bragg reflector (or other passive mode-locker based on film deposition technology) monolithically combined with a Fabry-Perot etalon and using temperature control for stabilization and tuning. The embodiment of this structure that we fabricated consists of a GaAs wafer (referred to as a substrate) with both surfaces polished, as shown in Fig 1. On one side (called top surface) is grown epitaxial films which

form a structure identified in the literature as a saturable Bragg reflector (SBR), consisting of a distributed Bragg reflector (DBR) with the topmost layer containing a quantum-well saturable absorber. The other surface of the substrate (called back surface) has a partial reflectivity which, combined with the substrate interior and the back side of the DBR, form an etalon. The device is mounted on a temperature-regulated surface to control the optical path length of the substrate which affects the etalon free spectral range (i.e. spacing of resonant modes).

The SBR section of this device can include all variants that are known in the literature, e.g. multiple quantum wells, or different placement of quantum wells in the SBR stack, etc. Also different types of structures can be used in place of the SBR, such as the anti-resonant Fabry-Perot saturable absorber (AFPSA), the low-finesse AFPSA, the semiconductor saturable absorber (SESAM), and the hybrid saturable reflectors which are types of devices described in the literature.

2. SATURABLE REFLECTOR APPARATUS

Fig. 1A depicts a Saturable Reflector apparatus according to a first embodiment of the present invention. The apparatus 100 generally comprises a saturable reflector 110 attached to a substrate 120. The apparatus 100 may further include a mounting plate 130 attached to reflector 110 or substrate 120 by any suitable means, such as a solder, glue or mechanical clamp. The saturable reflector includes a saturable absorber layer 116. The reflector 110 may be a metal or dielectric film. Alternatively, the reflector 110 may be a Bragg stack as depicted in Fig. 1A. The Bragg stack 110 typically comprises narrow bandgap layers 112 and wide bandgap layers 114. Narrow bandgap layers 112 are typically made of Gallium Arsenide (GaAs) or some other narrow bandgap semiconductor material. Wide bandgap layers 114 are typically made of Aluminum Arsenide

(AlAs). Alternatively, other suitable wide bandgap semiconductor materials such as InGaAs or InP may be used for wide band gap layers **114**. The narrow bandgap layers **112** and wide bandgap layers **114** alternate in the stack **110**. The stack typically contains about 5 to 100 layers of each type, typically 30. Each layer has an optical thickness of approximately 1/4 of the desired wavelength of operation, e.g. about 0.08 microns thick for GaAs and 1 micron radiation. The stack **110** is typically about 1 micron thick overall. The stack **110** includes a saturable absorber layer **116** in one of the narrow bandgap layers **112**. In an exemplary embodiment, the saturable absorber layer **116** is a layer of Indium Gallium Arsenide (InGaAs) approximately 10 nm thick, which forms a quantum well. Alternatively, the saturable layer **116** may include multiple quantum wells of the type described above. The SBR section of this device can include all variants that are known in the literature, e.g. multiple quantum wells, or different placement of quantum wells in the SBR stack, etc. Also different types of structures can be used in place of the SBR, such as the antiresonant Fabry-Perot saturable absorber (AFPSA), the low-finesse AFPSA, the semiconductor saturable absorber (SESAM) and the hybrid saturable reflector which are types of devices described in the literature.

The substrate **120** is typically GaAs about 100 to 1000 microns thick. The substrate has a front surface **122** and a back surface **124**. The reflector **110** is typically attached to the front surface **122**. The reflector **110** may alternatively be attached to the back surface **124**. The front surface **122** and back surface **124** are generally parallel to each other. At least one of the two surfaces is modified to enhance an etalon effect due to light reflecting off the back surface **124** interfering with light reflecting off the front surface **122**. The etalon effect depends on the overall reflectivity, which is a combination of the

reflectivities of the front surface **122** and the back surface **124**.

With respect to substrate **120**, the meaning of the terms "front surface" and "back surface" are, of course, dependent upon the direction of incidence of light. For example, if light traveling from right to left is incident upon the reflector **110** from the right in Fig. **1A**, the surface **122** is the front surface and surface **124** would be the back surface. Alternatively light traveling from left to right may be incident upon surface **124** from the left. In such a case surface **124** would be the front surface and surface **122** would be the back surface. Both configurations are within the scope of the embodiments of the present invention. Therefore, the terms front surface and back surface may be used interchangeably without loss of generality.

There are several ways in which the surfaces might be modified. For example, the back surface **124** might be polished to enhance Fresnel reflection. Generally, the back surface **124** is polished so that the surface does not deviate locally from flatness by more than about $1/4$ of the wavelength of the radiation incident on it. More preferably, the back surface **124** is polished to within about $1/8$ of the wavelength. Alternatively, the substrate **120** may be attached to a support plate (not shown) by an adhesive that affects the reflectivity of the back surface **124**. In a preferred embodiment, a reflective coating **126** of dielectric or metallic material is deposited on the back surface **124**. Preferably, coating **126** is made from a material that grows well on the substrate **120**. Similar modifications may be made to the front surface **122** to adjust the overall reflectance of the substrate **120**. Suitable materials for coating **126** include metals such as chrome and dielectrics such as Hafnium Oxide. Those skilled in the art will recognize that the reflectivity of the substrate **120** may also be modified by combinations of two or more of the methods described above and their legal equivalents.

The etalon effect may be tuned by adjusting an optical thickness of the substrate **120** between the front and back surfaces. The optical thickness generally depends on the product of a thickness **t** and an index of refraction **n** of the substrate **120**.

5 The expression for the optical thickness may be more complicated to account for variations of **n** with location within substrate **120** or with wavelength of incident radiation. The optical thickness may be adjusted by changing **t** or **n** or both. For example, changing the temperature of the substrate **120** changes
10 both **t** and **n** in a known fashion that depends on the substrate material. Thus, the etalon effect of SBR **100** may be tuned, for example, using a heater or cooler element incorporated into mounting plate **130** and temperature controller.

15 Alternatively, the substrate **120** may be made of a material that exhibits piezoelectric, electro-optic or magneto-optic effects, so that any one or more of these effects may be used to tune the etalon effect of SBR **100**. In the piezoelectric effect, an electric field applied to the material of substrate **120** produces a mechanical strain that alters the physical dimensions of
20 substrate **120**, e.g. the thickness **t**. In the electro-optic effect, an electric field applied to the material of substrate **120** changes the index of refraction **n** in a known fashion that depends on the electric field. In the magneto-optic effect, a magnetic field applied to the material of substrate **120** changes
25 the index of refraction **n** in a known fashion that depends on the magnetic field.

Thus an etalon tunable optical system may be built from SBRs of the type shown in Fig. **1A** with fewer parts and considerably easier alignment than a device using a separate etalon. This
30 reduces the cost and complexity of any optical device that uses the SBR **100** with etalon tuning.

It is useful to compare and contrast the first embodiment of the present invention with a prior art mode-locking device that contains an etalon. Fig. 1B depicts a prior art mode locking device 101. The device 101 generally comprises a distributed Bragg reflector (DBR) 111, such as a Bragg stack of the type described above, attached to a substrate 121. An etalon 115 having an absorber layer 117 is attached to the front of the reflector 111. In the prior art device 101 the saturable absorber layer 117 is in between the two reflecting surfaces of the etalon 115. In the apparatus 100 of the first embodiment of the present invention, the saturable layer 116 is outside the etalon. This distinction is not trivial. The prior art etalon 115 is operated off resonance to lower the field strength in the saturable absorber layer 117. The etalon 115 of the prior art implementation of Fig. 1B is also typically spaced in antiresonance, which broadens the bandwidth of the reflectivity.

In the apparatus 100, by contrast, the etalon formed by the surfaces 122 and 124 of the substrate operates to control the resonance location relative to the laser gain peak and laser longitudinal modes. The interaction of this resonance with the gain spectrum is the key to the device operation. The principal is that the lower reflectivity of the etalon-enhanced saturable reflector on-resonance causes increased loss for that portion of the gain spectrum. This has the effect of flattening the gain and effectively increasing the bandwidth leading to shorter pulses. An additional difference is that the prior art etalon 115 is much thinner than the etalon formed by surfaces 122 and 124 of apparatus 100. The prior art etalon 115 is typically about 1 micron thick. Consequently, the fringes are as broad or broader than the typical laser line when the device 101 is used as a mode-locker in a mode-locked laser. The etalon of apparatus 100, by contrast, is typically several hundred microns thick. The etalon typically has a thickness large enough to give it a free spectral range (FSR) of order 1 GHz or greater.

For laser applications an FSR of order 1 GHz is of roughly comparable to or less than a typical laser gain spectrum. Multiple fringes may interact with the saturable absorber layer **116** of the apparatus **100**, to selectively shape the gain spectrum. In the prior art device **101** only one broad fringe interacts with laser gain and selective shaping of the gain spectrum does not occur.

3. LASER

The inventors have incorporated an etalon tunable SBR of the type described above with respect to Fig. **1A** into a mode-locked laser. The laser **200**, depicted in Fig. **2**, generally comprises an optical cavity **202**, a lasing medium **204**, and a pump source **206**. The laser **200** may optionally include a nonlinear medium **208**. The cavity **202** generally comprises two or more mirrors **210A-210C**, at least one of which includes an SBR **212** of the type described above with respect to Fig. **1A**. SBR **212** includes a Bragg Stack **213**, having a saturable layer **215**, attached to a substrate **217**. Light from the pump source **206** stimulates emission of laser radiation **207** of wavelength λ_L from the lasing medium **204**. Lasing medium **204** may be any medium capable of producing stimulated emission. Such a medium may be in the form of a solid, liquid or gas. Suitable media include doped crystals such as Nd:YAG and Ti:Sapphire, Nd:YLF, Nd:YVO₄, Nd:glass, fiber lasers and gases such as CO₂ and HeNe.

When the non-linear medium **208** is present, the laser radiation **207** may, for example, interact with the nonlinear medium **208** by a nonlinear parametric amplification effect to produce signal radiation **209** having a wavelength λ_s and idler radiation **211** having a wavelength λ_i . In general, λ_s , λ_p and λ_i are related by

$$(1) \quad \frac{1}{\lambda_L} = \frac{1}{\lambda_s} + \frac{1}{\lambda_i}.$$

Alternatively, the non linear medium **208** may interact with the pump radiation to produce second harmonic generation (SHG) effect. The nonlinear medium **208** may be in the form of a solid liquid or gas. Typically, the nonlinear medium **208** is a crystal containing a material chosen from the group consisting of Lithium Niobate (LiNbO_3), Lithium Tantalate (LiTaO_3), Lithium Borate (LiBO_3) periodically poled lithium niobate (PPLN), periodically poled lithium tantalate (PPLT) MgO:PPLN , KTP, PPKTP, RTA, BBO, MgO:LN , KTA, and PPRTA. Other suitable nonlinear media include Raman active, Brillouin active, or four-wave mixing media, which can also produce parametric amplification effects that happen to be nonlinear. Alternatively, one could use a span of optical fiber that exhibits Raman gain, Brillouin gain or four-wave mixing as the nonlinear medium **208**. The inclusion of the nonlinear medium **208** in the description of laser **200** is for the purpose of example and is in no way intended to limit the scope of the present invention.

Whether or not a non-linear medium is present, the cavity **202** may be any type of cavity structure having two or more mirrors. Suitable structures for the cavity **202** include Fabry-Perot, triangle, ring and bowtie cavities. The mirrors **210A-210C** may be flat or curved depending on the cavity design. Usually, one of the mirrors, e.g. **210A**, is partially reflecting so that radiation may be coupled in or out of the cavity **202**. One or more of the mirrors **210A-210C** may be movable so that a path length **L**, and therefore resonant frequency, of the cavity **202** may be tuned.

At least one of the mirrors, e.g. **210C**, includes an SBR **212**. The SBR **212** provides a nonlinear saturation response to incident

radiation that mode-locks the laser 200. As described above, the SBR 212 generally comprises a substrate having a front and back surfaces, and a Bragg stack, with a saturable absorber layer, attached to the front surface. At least one of the front and back surfaces of the substrate has been modified to enhance an etalon effect. The front or back surface may be modified according to any of the embodiments described above with respect to Fig. 1. Appropriate tuning of the optical thickness of the substrate 210 adjusts the transmission of the cavity 202. The transmission adjustment can affect the length of pulses of radiation emerging from the cavity 202. For example, when the transmission of the cavity 202 has a dip near the center of the spectrum of signal radiation 209, the pulse shortening is greatest.

As described above, the etalon effect may be tuned by adjusting an optical thickness between the front and back surfaces. Adjustment may be accomplished by any suitable means described above with respect to Fig. 1. In a preferred embodiment, a temperature control element 214 thermally coupled to the SBR 212 tunes the etalon effect of the SBR 212. The temperature control element 214 may be any type of device used for radiatively, conductively or convectively transferring heat into or out of the SBR 212. For example, the heater element 214 may be a resistive element Ohmically heated by an electric current. Alternatively, the temperature control element 214 may be a cooling element that cools the SBR 212 by convective fluid flow or Peltier effect. A temperature controller 216 coupled to the temperature control element 214 regulates the amount of heat transferred to or from the SBR 212. Such a temperature controller may operate by ~~X, X~~ a feedback loop to control a power supply 218. The feedback loop operates to optimize a spectrum of the signal radiation 209. The feedback loop may be coupled through an optical sensor that monitors the signal radiation 209

or a temperature sensor that measures the temperature of the substrate **212**. Such a feedback loop may be implemented in hardware or software or some combination of both. To tune the etalon effect, it is often desirable to maintain the temperature of substrate **212** to within about ± 0.1 C° of a desired target temperature. Prior art temperature tuning of the SBR exciton effect, by contrast, may only require that the substrate temperature be maintained within ± 1 C°.

4. EXPERIMENTAL RESULTS

A physical example of a specific implementation of the embodiments of the invention illustrates the device operation. A laser incorporating the features described above used an SBR fabricated by Epitaxial Products Inc. (EPIQ9802414 #1) on top of a 0.5 mm thick GaAs wafer substrate polished on both surfaces. The SBR in this example is in the form of a distributed Bragg reflector (DBR). An etalon is formed by the DBR on the top surface and the polished back surface. The free spectral range of the etalon was $c/2nL = 72$ GHz (where $n=4.16$ is the index of refraction, c is the speed of light, and L is the substrate thickness). The Fresnel reflectivity of the polished back surface is $[(n-1)/(n+1)]^2 = 37\%$, and the finesse is ≈ 10 , assuming 97% reflectivity of the DBR ($\text{finesse} = 2\pi/\delta_c$ where δ_c is the total fractional power loss per one round trip).

Fig. **4** depicts a sketch of laser gain line shape juxtaposed with the etalon reflectivity spectrum (not to scale) for a mode-locked laser of the type shown in Fig. **2**. The values shown represent the parameters of our experimental realization. By aligning an etalon reflectivity minimum with the gain peak, the peak is suppressed and the laser gain line shape is flattened. The decrease in reflectivity of the etalon on resonance increases the loss to the laser cavity. If this point of higher loss is aligned with a peak in the laser gain, then the gain

profile is flattened, as shown in Fig. 4, by comparing the solid and dashed lines representing the laser gain profile. The laser gain line shape shown in this figure is a representative sketch, not necessarily an actual line shape for any particular laser.

5 The asymmetry such as shown here is suggested by line shapes observed with a scanning Fabry-Perot interferometer (see Fig. 6A-6B).

The above described device used temperature to control the etalon resonance. Temperature tuning of SBRs is known in the prior art. However, in the prior art, temperature tuning is used to control the exciton absorption peak relative to the gain peak of the laser medium which is a different effect than etalon tuning. Changing the exciton absorption peak by temperature affects the onset of mode-locking and to some extent affects the pulse width . We see this effect in our device also, typically causing shortening of the pulse by $\sim 5\%/10^\circ\text{C}$ as shown in Fig 3. The effect of temperature change on the etalon produces further shortening of the pulse length and it has a faster tuning rate compared to that of exciton peak tuning, typically $\sim 20\%/1^\circ\text{C}$ as also seen in Fig 3. The gradual decrease in the average pulse width (shown by the dashed line) is due to exciton tuning with an initial rate of approximately $-5\%/10^\circ\text{C}$. The steep decrease occurring every 3°C interval is due to etalon tuning, at a rate of approximately $-20\%/1^\circ\text{C}$. The pulse length change due to etalon tuning shows up as a modulation under the envelope of the tuning of the exciton absorption peak. Because the tuning rate of the etalon is so much greater than that of the exciton absorption, they are clearly distinct and separate effects.

Fig. 5 shows a detail of two portions of Fig 3. The etalon resonance is characterized by regions of a stable, clean pulse separated by regions of a noisy pulse. In the stable regions, pulse shortening occurs as the etalon peak moves across the gain line shape when the temperature changes. In this experiment,

the regions of stable operation are wider at higher temperatures. The pulse behavior as a function of temperature shows that the etalon tuning behavior is observed in a regime where the pulse is clean and well-formed, which is bracketed by a region in which the pulse is noisy. Note that the temperature range for the stable, clean pulse increases at higher temperature under these particular experimental conditions. Since the sensitivity of pulse width change vs. temperature change is approximately constant within the resonance regions, operating at higher temperature gives greater tolerance for pulse stability. The slope of 2% for 0.1 °C temperature change within the etalon resonance makes the device relatively straightforward to stabilize with available temperature controllers. Thus a typical concern about the difficulty of stabilizing an etalon in a laser cavity is a manageable issue for our device in practical operation.

Figs. 6A-6B depict the effect of removing the etalon enhancement by operated the device with a sanded back surface to eliminate the etalon resonance, as shown in Fig. 6. In that condition, the pulse width was typically 2 times longer than when we used etalon enhancement for otherwise identical laser conditions. Using etalon enhancement, we found that the best pulse width for this device and the parameters that we investigated was 29 ps at 99.7 °C.

Thus, an etalon-tunable mode-locked laser may be produced by suitable modification of one or more surfaces of an SBR substrate and tuning the thickness of the substrate. The etalon tuning capability is obtained at a nominal cost without adding to the complexity of the laser. Embodiments of the present invention allow passively mode-locked lasers to produce shorter pulses without introducing more components. The monolithic approach avoids the insertion of additional loss into the laser cavity which would degrade the laser output power. The device

has cost advantages in that it is made with only a few simple additions to the basic passive mode locker, which costs less than a discrete implementation. Advantages in manufacturability are the parts count is lower with a monolithic implementation, and there are fewer surfaces that can be damaged. The temperature control of this etalon is simpler than a discrete implementation because the entire face can be mounted in a temperature-controlled surface since the device is used in reflection rather than transmission.

Mode-locked lasers are important for efficient frequency conversion and other applications requiring high peak power or short pulses. Applications for sources using efficient frequency conversion include laser-based displays using red, green, and blue lasers, photoresist exposure and defect identification for printed circuit board and LCD flat panel fabrication using UV sources, semiconductor wafer inspection using UV sources, and infrared countermeasures. Applications for short pulse and high peak power sources include machining, semiconductor test and measurement, photodynamic therapy, two-photon imaging, and electro optical sampling. Most of these applications benefit from shorter pulses which are provided by enhancement of the passive mode-locker with an integrated etalon. Alternatively longer pulses can also be created if needed for specific applications.

It will be clear to one skilled in the art that the above embodiment may be altered in many ways without departing from the scope of the invention. Accordingly, the scope of the invention should be determined by the following claims and their legal equivalents.